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CARBON FOOTPRINTING

Time-adjusted global warming potentials for LCA and carbon footprints

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Abstract
Purpose The common practice of summing greenhouse gas (GHG) emissions and applying global warming potentials (GWPs) to calculate CO_2 equivalents misrepresents the global warming effects of emissions that occur over a product or system's life cycle at a particular time in the future. The two primary purposes of this work are to develop an approach to correct for this distortion that can (1) be feasibly implemented by life cycle assessment and carbon footprint practitioners and (2) results in units of CO_2 equivalent. Units of CO_2 equilavent allow for easy integration in current reporting and policy frameworks.
Methods CO_2 equivalency is typically calculated using GWPs from the Intergovernmental Panel on Climate Change. GWPs are calculated by dividing a GHG's global warming effect, as measured by cumulative radiative forcing, over a prescribed time horizon by the global warming effect of CO_2 over that same time horizon. Current methods distort the actual effect of GHG emissions at a particular time in the future by summing emissions released at different times and applying GWPs; modeling them as if they occur at the beginning of the analytical time horizon. The method proposed here develops time-adjusted warming potentials (TAWPs), which use the reference gas CO_2, and a reference time of zero. Thus, application of TAWPs results in units of CO_2 equivalent today.
Results and discussion A GWP for a given GHG only requires that a practitioner select an analytical time horizon. The TAWP, however, contains an additional independent variable; the year in which an emission occurs. Thus, for each GHG and each analytical time horizon, TAWPs require a simple software tool (TAWPv1.0) or an equation to estimate their value. Application of 100-year TAWPs to a commercial building's life cycle emissions showed a 30 % reduction in CO_2 equivalent compared to typical practice using 100-year GWPs. As the analytical time horizon is extended the effect of emissions timing is less pronounced. For example, at a 500-year analytical time horizon the difference is only 5 %.
Conclusions and recommendations TAWPs are one of many alternatives to traditional accounting methods, and are envisioned to be used as one of multiple characterizations in carbon accounting or life cycle impact assessment methods to assist in interpretation of a study's outcome.

Keywords Climate change · Cumulative radiative forcing · Emissions timing · Greenhouse gas · GWP · Impact assessment

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1 Introduction

The treatment of greenhouse gas (GHG) emissions in carbon footprints and life cycle assessment (LCA) has typically been limited to the application of global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) to GHG emissions summed over a product or system's life cycle. Thus, GHG accounting methods, including those in LCA, have almost universally ignored

the effect of GHG emissions timing. This practice distorts the actual global warming effect of emissions over time, particularly when shorter analytical time horizons are considered.

The importance of emissions timing along with potential solutions has been recognized previously in the context of LCA and carbon accounting (e.g., Clift and Brandao 2008; O'Hare et al. 2009; Kendall et al. 2009; Levasseur et al. 2010; Müller-Wenk and Brandão 2010; Courchesne et al. 2010; Schwietzke et al. 2011; Peters et al. 2011; Levasseur et al. 2012; Kendall and Price 2012). The problem has also been addressed in the fields of climate change science and mitigation, including Moura-Costa and Wilson (2000), Fearnside et al. (2000), Fearnside (2002), Sygna et al. (2002), Fuglestvedt et al. (2003), and Shine et al. (2005), to name a few. The carbon footprinting standard PAS2050 has also acknowledged this problem and includes optional calculation processes for emissions timing (British Standards Institution 2008, 2011).

Many of the methods previously offered to correct for emissions timing in LCA build on the IPCC's indicator of global warming, cumulative radiative forcing (CRF), which is the basis for GWP calculations. GWPs are calculated as the ratio between the CRF of a non-CO_2 GHG over a defined analytical time horizon and the CRF of CO_2 over that same time horizon. When GHGs are summed over a life cycle or other defined time horizon and GWPs applied, all emissions are essentially treated as if they occur at the same time. In this paradigm, the global warming effect of these emissions at a defined point in the future are misrepresented over typical time scales (e.g., 100 years), though at longer time horizons this distortion is less pronounced, and at an infinite time horizon, non-existent.

The method proposed here builds on previously proposed methods, using normalized CRF as an indicator for the relative effect of GHG emissions occurring over time. Its primary contributions are an actionable approach to address emissions timing that yields units compatible with the existing reporting paradigm of CO_2 equivalent (CO_2e). The proposed approach develops equivalency potentials referred to as time-adjusted warming potentials (TAWPs). The TAWP includes a reference gas, CO_2, and a reference time, year 0 (i.e., today). Thus, application of a TAWP yields units of CO_2e today.

1.1 The problem of emissions timing

The common practice of reporting summed GHG emissions in units of CO_2e may over- or underestimate the warming potential of those emissions over typical analytical time scales depending on the profile of emissions. This distortion occurs because the CRF of an emission is evaluated over a predefined time horizon, often 100 years, but emissions occurring at different times are simply summed together; despite that their end points of analysis are different.

For example, using a 100-year GWP, an emission occurring in 2012 will be evaluated until 2112, and an emission occurring in 2022 will be evaluated until the year 2122. When they are added together, information about the end-point of analysis is lost, and emissions profiles with different effects at different times are treated equal. This method distorts our understanding of the magnitude global warming at a particular time in the future. Put another way, it distorts the accounting of emissions flows by ignoring information about when they occur. This is problematic because the impacts of emissions at different points in time have different implications for climate change processes and impacts.

However, assessing CRF or some other metric related to the impact of an emission at a particular time in the future means that emissions occurring at different times will be valued over different time horizons. This can lead to another kind of distortion—namely the preference for pushing emissions into the future, so that their impacts will be valued (in the case of CRF, integrated) over shorter time horizons. This is an unavoidable trade-off in selecting between a metric that accounts for emissions timing by considering a fixed point in time in the future like the TAWP, versus a metric that evaluates emissions occurring at any time over identical time periods like GWP.

To demonstrate how simple summation distorts the CRF over typical analytical time horizons (e.g., 20–500 years), we can compare three emissions profiles, all of which sum to net emissions of 1,000 kg of CO_2. Recall that in most typical carbon accounting and LCA practices, these emissions would be summed without regard for timing; in other words, they would be considered equal. The following three profiles are considered: profile 1 is dominated by upfront emissions (1,000 kg in year 0, no emissions in future years), profile 2 simulates constant emissions over a 20-year life cycle (50 kg of CO_2 per year, for 20 years), and profile 3 reflects a product or material that receives significant recycling credits at the end-of-life (2,000 kg CO_2 in year 0, −1,000 kg after 20 years). Profile 1 is how current LCA and footprinting practices represent all three profiles.

Figure 1a shows the CRF of these three emissions profiles for a 100-year time horizon, and Fig. 1b shows the same for a 500-year time horizon. The CRF calculations shown in Fig. 1a and b are based on a model developed using radiative efficiency and lifetime data from the IPCC (2011) and methods described in Shine et al. (2005) for calculating absolute global warming potentials.

Comparison of Fig. 1a and b demonstrate that differences in CRF for the three profiles are more pronounced for the shorter 100-year time frame. Thus, emissions timing is likely to be more important when shorter time horizons of

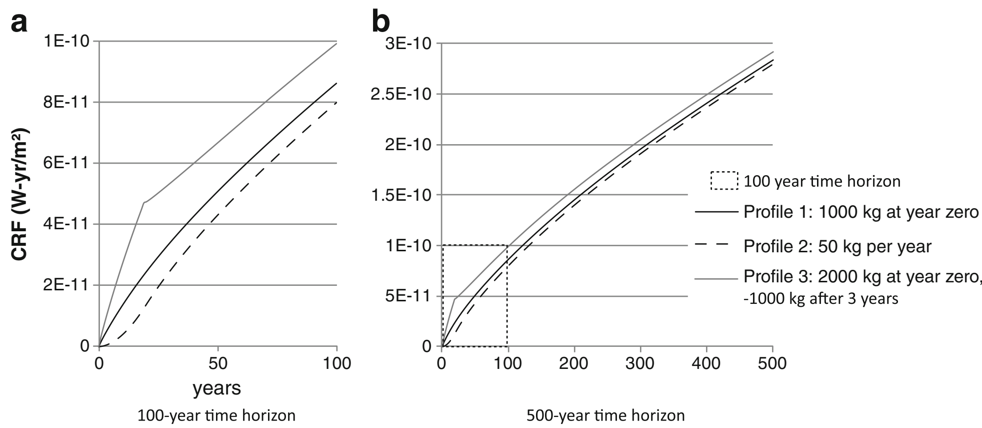

Fig. 1 CRF of three emissions profiles with net emissions of 1,000 kg CO_2

analysis are used; a phenomenon observed in previous studies (e.g., Levasseur et al. 2012).

Summing emissions over long life cycles and treating them as if they occur immediately (profile 2) overestimates their global warming effect, at least as evaluated over time horizons of around 100 years. As evidenced in Fig. 1b, the difference between profiles 1 and 2 is quite small at 500 years.

Profile 3, which includes a significant recycling credit, shows that crediting recyclable materials with avoided emissions as if they occur immediately significantly overestimates the global warming benefits of recycling, particularly if the time between production and recycling is long. Again, this difference is significantly more pronounced at the 100-year timescale than the 500-year timescale, where all three profiles are quite similar.

1.2 Previous methods for addressing emissions timing in LCA

A number of recent studies have proposed methods for addressing emissions timing in LCA. Most of the proposed methods and metrics are based primarily on CRF, though some have proposed metrics that address temperature change. Many of these articles have formed their discussion of emissions timing largely, though not exclusively, in the context of biofuel production and land-use change or temporary carbon storage.

O'Hare et al. (2009) proposed a new metric, the fuel warming potential (FWP), tailored to the problem of comparing the global warming effect of biofuels to petroleum-based fuels. The metric is based on the ratio of CRF between a biofuel and a reference fuel, which should be its fossil fuel counterpart. They found that by using the FWP the performance of corn ethanol decreased compared to gasoline, because of upfront emissions caused by land-use change. O'Hare et al.'s CRF model accounted only for CO_2 and modeled the other GHGs in their CO_2e values. They argued that the dominance of CO_2 emissions in both the petroleum and bio-based fuel life cycles meant this approximation would not introduce significant errors.

Kendall et al. (2009) proposed a scaling factor, referred to as the time correction factor (TCF) for the special case of amortized emissions in LCA, which yields time corrected emissions intensity estimates (e.g., CO_2e/MJ). Like O'Hare et al., Kendall et al.'s method was based on the CRF of CO_2 and not other GHGs. This scaling factor is tailored for application to upfront emissions that are amortized over a prescribed time horizon and assures that the CRF of the amortized emission is equal to the CRF of the actual emission at the end of the amortization period. An important point is that the analytical time horizon is equal to the amortization period in this approach, which limits the flexibility of its use. Kendall and Price (2012) enhanced the TCF proposed in Kendall et al. (2009) by making the analytical time horizon independent of the amortization period, and addressing both amortized production and end-of-life CO_2 flows.

Levasseur et al. (2010) proposed dynamic characterization factors (DCFs) to replace the more commonly used unit of CO_2e in LCA impact assessments. Their method breaks the life cycle into 1-year time steps and adds the instantaneous DCF for each time step for each emission, and considered CO_2 as well as other long-lived GHGs. This approach is more generalizable than O'Hare et al.'s FWP tailored to transportation fuels, and Kendall et al.'s TCF tailored to amortized upfront emissions. Despite this benefit of generalizability and the conceptual soundness of the DCF, Levasseur et al.'s approach does not provide a straightforward process for other LCA practitioners to implement their method.

Müller-Wenk and Brandão (2010) developed a tailored metric to address CO_2 emissions from soil and vegetation caused by land-use change and land occupation. They develop a carbon equivalency factor relating CO_2 emissions from land transformation to CO_2 emissions from fossil fuel combustion. The equivalency factor accounts for the predicted duration of emissions from land transformation in the atmosphere compared to fossil CO_2 emissions.

Courchesne et al. (2010) examined ethanol production and use in the context of LCA using the Lashof method (Fearnside et al. 2000), which characterizes GHGs in the unit of megagram-year. They also report outcomes based on a reduction coefficient, which is based on the difference in CRF between a biofuel and a baseline system that is assumed to be a petroleum-based fuel.

Like O'Hare et al., Schwietzke et al. (2011) sought to address the particular case of corn ethanol in their study and proposed an emissions timing factor (ETF). They concluded that emissions timing was less important in the biofuel life cycle than previous studies had suggested. Schwietzke et al. also estimated temperature change. Similar to the conclusions they reached based on the ETF, they found temperature change differences due to emissions timing to be small for the case of corn ethanol.

Peters et al. (2011) expanded the discussion of time and GWPs to include short-lived climate forcers (SLCFs) and alternative metrics including those based on temperature change, rather than CO_2e, along with radiative forcing-based metrics that address emissions timing. They applied these metrics to transportation emissions. Their conclusions highlight the need to expand the emissions included in typical global warming calculations to include SLCFs, and the need for LCA to consider alternatives to current metrics, such as temperature change. In addition, the authors point out that SLCFs are more influential when shorter time horizons are considered and may be particularly important if the rate of temperature change from global warming is considered, rather than just peak temperature change.

Peters et al. are not alone in their call for temperature change metrics as alternatives to radiative forcing-based metrics. Shine et al. (2005, 2007) proposed the use of global temperature change potentials (GTPs). GTPs assess temperature change at a specific time in the future. GTPs offer some important differences compared to methods based on CRF. For example, as indicated in Shine (2009), because CRF is based on an integrated radiative forcing, the effect of, for example, a short-lived GHG never disappears, even long after it has left the atmosphere. This is because GTP is based on the climate's response to radiative forcing, which is an instantaneous rather than cumulative metric.

Levasseur et al. (2012) demonstrated the influence of selecting an accounting time horizon for climate change effects for assessing the benefits of temporary carbon storage. As Levasseur et al. note in their article, temporary storage of carbon is equivalent to delaying emissions. Using the Lashof method and related equations developed in Clift and Brandao (2008), they varied time horizons from 20 to 1,000 years and showed that the benefits of storing 1,000 kg of carbon for 50 years could be assessed at a high of 1,000 kg CO_2e for analytical time horizons ≤50 years, to a low of 41 kg CO_2e for a time horizon of 1,000 years. Among other outcomes, this study underscores the challenge of using any method where an analytical time horizon must be selected because it leads to a zero value for emissions of radiative forcing occurring after the end of the analytical time horizon.

The question of temporary carbon storage was also addressed in an expert workshop convened by the European Commission in 2010 (Brandão and Levasseur 2011). Conclusions of the workshop stressed the ongoing debate over whether accounting for temporary carbon storage should be included in LCA and carbon footprinting, as well as the debate over selection of an analytical time horizon. Because there is no consensus on the issue, the workshop report concludes that practitioners should ensure transparency in the methods and choices made, and that both short and long time horizons be applied if temporary carbon storage is going to be accounted for. Moreover, the workshop report concludes that alternative indicators for climate change effects should be considered and further researched, such as those related to temperature change.

In addition to articles and reports addressing the issue of emissions timing, *PAS2050:2011*, the most recent carbon footprinting standard from the British Standards Institution (2011), provides guidelines for inclusion or exclusion of stored carbon and an optional method for weighting emissions based on their timing (*Annex E* in *PAS2050:2011*). *PAS2050:2011* proposes two methods for addressing emissions timing; a "general case" which is the weighted average time an emission will be in the atmosphere assuming a 100-year time horizon for accounting, and a "specific case" for a single pulse emission occurring within 25 years of the start of a product's life cycle (p. 33). These methods draw on the equations described in Clift and Brandao (2008). The specific case is based on the first term in the Bern cycle atmospheric decay equation for CO_2; thus, it does not provide methods tailored to non-CO_2 GHGs. The standard cautions against using these methods to analyze products or systems where non-CO_2 GHGs make significant contributions to the carbon footprint.

These articles and reports demonstrate the rich and evolving landscape of concepts and methods proposed by the research community to address the problem of emissions timing and the limitations of adopting IPCC GWPs and simple summation of emissions. Newly developed methods, such as the TAWP, should clearly define their purpose and additional contribution to the existing landscape. The primary contributions of the TAWP method are as follows; (1) development of an actionable and easy-to-use method for LCA and carbon footprint practitioners and (2) a time-corrected metric in units of CO_2e to facilitate integration in current regulations, standards, and practices.

2 Methods

2.1 Development of a time-corrected CO_2-equivalent metric

The time-corrected CO_2e method proposed here is premised on the same indicator as the IPCC's GWP, CRF, and like GWP it is applied as a multiplier to a mass of some GHG emission. Equation (1) shows the method for generating GWPs. The GWP calculation requires the selection of an analytical time (AT) horizon for calculating CRF. The IPCC reports GWPs for three analytical time horizons, 20, 100, and 500 years, but GWPs can be calculated for any analytical time horizon.

As evidenced by the integration boundaries in Eq. (1), the GWP equation evaluates emissions in the numerator over a period of AT years, so when they are applied to emissions occurring in the future (or past) they misrepresent CO_2 equivalency at a particular time in the future.

$$\mathrm{GWP_{AT}} = \frac{\int_0^{\mathrm{AT}} \mathrm{RF}_i \mathrm{d}t}{\int_0^{\mathrm{AT}} \mathrm{RF_{CO_2}} \mathrm{d}t} = \frac{\mathrm{CRF}_i}{\mathrm{CRF_{CO_2}}} \tag{1}$$

where AT is the analytical time horizon; RF is radiative forcing, which is a function of a gas's decay rate from the atmosphere and its radiative efficiency; and i is the GHG that will be converted into CO_2e.

To develop a GWP-like factor that accounts for the time an emission occurs, emissions timing must be introduced as an additional variable. To achieve this, the integration boundaries of the numerator in Eq. (1) can be changed to reflect the actual timing of an emission, while maintaining the integration boundary of the denominator. If an emission occurs y years in the future, then it will be in the atmosphere AT−y years at the end of the AT. Thus, the updated equivalency factor will account both for the difference in radiative forcing between the reference gas and the GHG of interest (CO_2 and i), and the difference in their timing (year 0 and y). This new equivalency factor, referred to as the TAWP, is thus defined based on a reference gas, CO_2, and a reference time, year 0 (Eq. (2)).

$$\mathrm{TAWP} = \frac{\int_0^{\mathrm{AT}-y} \mathrm{RF}_i(t) \mathrm{d}t}{\int_0^{\mathrm{AT}} \mathrm{RF_{CO_2}}(t) \mathrm{d}t} \tag{2}$$

TAWPs correct for the difference in global warming effect over a particular time horizon between emissions occurring in the future and an emission of CO_2 today, and thus require the selection of an analytical time horizon. As observed by previous researchers (for example, Shine 2009 and Levasseur et al. 2012, to name but a few), selection of any particular analytical time horizon is inherently subjective, and it may be preferable to use multiple analytical time horizons instead of a single one in a study (Brandão and Levasseur 2011). Rather than recommending a particular analytical time horizon, the TAWP calculation tool provides results for a variety of analytical time horizons between 20 and 500 years.

Table 1 One kilogram of emissions (CO_2, CH_4, and N_2O) 10 years in the future represented as CO_2e today

Analytical time horizon	CO_2 as kg CO_2e today	CH_4 as kg CO_2e today	N_2O as kg CO_2e today
20	0.578	52.4	158
30	0.739	53.3	214
50	0.855	42.0	261
100	0.930	25.4	281
500	0.987	7.68	154

To generate TAWPs, a CRF model using IPCC's *Fourth Assessment Report's* estimates of lifetimes, radiative efficiencies, and indirect effects (for methane only) of the GHGs modeled in this study was developed (IPCC 2011). One shortcoming in the CRF model is that the IPCC reports a limited number of significant digits, leading to small differences between the CRF model used to generate TAWPs and the IPCC's reported GWPs. Users of TAWPs will see this difference if they use the TAWP to estimate CO_2e for an emission in year 0, for example.

The introduction of a new variable (y in Eq. (2)) means that TAWPs cannot be defined by a simple scaling factor. Thus, an Excel-based program, TAWPv1.0, was developed to automate the calculation and is provided in the Online resource 1 in the Electronic Supplementary material (ESM).

There may be times where using the automated calculator is not convenient—for example in an existing spreadsheet model or other tool. To facilitate the use of TAWPs in

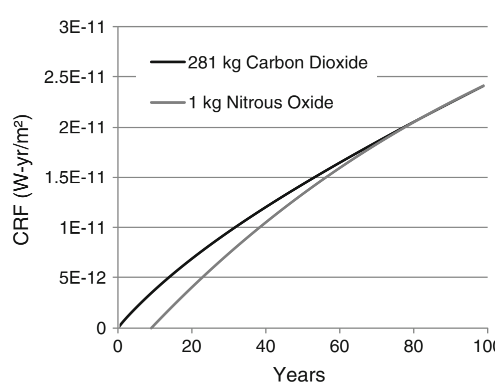

Fig. 2 CRF of 1 kg N_2O 10 years in the future and its CO_2e calculated using TAWP_{100}

Table 2 Comparison of GWP, TAWP, and PAS2050 methods (t CO_2e)

	GWP_{100}	$TAWP_{100}$	$TAWP_{500}$	PAS2050 (general case)	PAS2050 (specific case)
Full 75 years of building life cycle	135,000	93,315	127,591	83,884	–
First 25 years of building life cycle	46,061	41,965	–	–	41,749

such situations, best-fit linear or polynomial equations for TAWPs for 20, 30, 50, 100, and 500 year time horizons for CO_2, CH_4, N_2O, SF_6, PFC-14, PFC-116, and HCFC-22 are provided in Online resource 2 in the ESM. Lower-order polynomials were favored where possible, to ease the burden of implementation. Because the equations are best-fit approximations, the preprogrammed TAWP model provided in the electronic supplemental material should be used when possible.

3 Results and discussion

3.1 Application of the TAWP

TAWPs are applied just as a GWP is applied, as demonstrated in Eq. (3):

$$CO_2e = \text{mass of emission}_i \times TAWP_{AT}(y) \tag{3}$$

Table 1 shows the CO_2e today for 1 kg of CO_2, 1 kg CH_4, and 1 kg N_2O emitted 10 years in the future, for various analytical time horizons from 20 to 500. Table 1 demonstrates two important trends. First, for CO_2, as the analytical time horizon grows, CO_2e today is closer to the mass of CO_2 emitted in year 0 (1 kg). Meaning that accounting for timing is less important at longer analytical time horizons. This trend is mirrored for CH_4 and N_2O, where the CO_2e for a 500-year time horizon are very close to the IPCC GWP_{500} values of 7.6 and 153, respectively.[1]

Figure 2 shows what the CO_2e values in Table 1 mean in practical terms by illustrating that the CRF of 281 kg of CO_2 occurring in year 0 and 1 kg of N_2O occurring 10 years later are equal at the end of a 100-year time horizon, validating the 100-year CO_2e estimate for N_2O emitted in year 10.

3.2 Application of TAWPs to case studies

To illustrate a life cycle where the timing of emissions will effect CO_2e calculations significantly, we examine the case of a commercial building. Commercial buildings are long-lived, and their life cycle GHG emissions tend to be dominated by their use phase, meaning that emissions occur throughout the entire life cycle.

Using a simplified interpretation of findings from Scheuer et al. (2003), who found that a commercial building generated 135,000 t CO_2e over its 75-year life, we assume that material production and construction occurs in year 0 and is equal to 4,360.5 t CO_2e, the use phase generates 1,737.5 t CO_2e per year for 75 years, and decommissioning accounts for only 324 t CO_2e. While we cannot separate CO_2e emissions into their constituent GHGs because of how they are reported in the article, we assume that the dominant emission is CO_2 and we treat all emissions as CO_2.

Using the TAWP model, we calculate a time-adjusted CO_2e for a 100-year analytical time horizon of 93,315 t CO_2e. This means that the emissions occurring over the entire building life cycle are the equivalent of releasing 93,315 kg CO_2e in year 0; more than 30 % lower than a simple summation of life cycle emissions. An analytical time horizon of 500 years results in 127,591 t CO_2e, much closer to the simple summation of GHG emissions (135,000 t CO_2e). These results are shown in Table 2.

Despite providing a great deal of detail in their results, Scheuer et al. reported only CO_2e, not the actual flows of each GHG that were tracked. The timing of emissions was not reported either; rather, emissions timing was approximated based on the description of the building life cycle. This highlights the additional reporting requirements required in LCAs that consider emissions timing, which increases the reporting burden on practitioners. In fact, even studies that do not consider emissions timing might benefit from including more detailed reporting on the flows of individual GHGs and their timing to support future meta-analyses or future comparisons where emissions timing or other alternative global warming metrics are applied.

Other cases where timing is important may include estimation of global warming benefits of carbon sequestration strategies or estimating the benefits of avoided emissions in consequential LCAs. In both cases, negative flows of emissions are considered, but the same effects regarding emissions timing are present. Previous works have addressed this question in the context of forestry sequestration credits relative to avoided emissions (e.g., Moura-Costa and Wilson 2000, Fearnside et al. 2000).

[1] As indicated earlier, a lack of significant digits reported for radiative efficiency, lifetime, and/or indirect effects in the IPCC methodology leads to differences between the GWP and TAWP, even when in theory they should be identical. For example, the $TAWP_{500}(y=10)$ for methane should be identical to the IPCC GWP_{500}, but in fact it deviates by 0.08 kg CO_2e.

Here, we examine the global warming benefits of tree planting initiatives for carbon sequestration. Urban tree planting or reforestation initiatives may be sold or traded as carbon credits, but usually the credit is assigned as if sequestration occurs immediately. For a tree that sequesters approximately 40 kg CO_2 per year for 50 years, simple summation would lead to a sequestration credit of 2,000 kg of CO_2; however, if timing is considered and a 100-year analytical time horizon is used, this rate of sequestration is equivalent to 1,604.5 kg CO_2e sequestered today. If a shorter time horizon is used, such as a 50-year time horizon, the difference is even more dramatic, 1,107.4 kg CO_2e. Thus, when comparing the value of different sequestration credits, timing may play an important role in determining preferences for one strategy over another. This line of reasoning is similar to the discourse on temporary carbon storage in LCA.

3.3 Comparison to PAS2050:2011 methods

To compare the TAWP to another method that can practically be applied, the general case method in *PAS2050* is used to estimate time-adjusted life cycle CO_2e emissions for the same building from Scheuer et al. As shown in Table 2, the *PAS2050* general case method result in life cycle emissions of 83,884 kg CO_2e; significantly lower that the $TAWP_{100}$ results.

The specific case method provided in *PAS2050* is more accurate than the general case, but must be more narrowly applied to emissions occurring within 25 years, meaning that it cannot be used to characterize the full building life cycle. However, to test the difference between the TAWP and the *PAS2050* specific case method, the two methods can be compared over the first 25 years of the building life. Using the specific case method, the difference with the TAWP is small, about 0.5 %. This implies that for cases where (1) emissions occur within 25 years and (2) emissions are entirely or largely CO_2, the *PAS2050* specific case equation and TAWP will result in similar outcomes.

For life cycles where non-CO_2 emissions are important, the TAWP provides improved accuracy, since *PAS2050* methods are based solely on CO_2. For example, if a system releases 100 kg of CH_4 per year for 10 years, the specific case methods from PAS2050 will result in CO_2e emissions of approximately 19.1 t, 25 % lower than outcomes from $TAWP_{100}$ calculations.

4 Conclusions and future work

The TAWP is one of many proposed metrics that address the problem of emissions timing in carbon accounting and LCA. Its particular contribution to the landscape of global warming metrics is (1) the provision of a simple open-source calculation tool (or best-fit equations) for application to CO_2 and non-CO_2 long-lived GHGs, and (2) conformance to the common unit of CO_2e. The TAWP may be particularly valuable as an additional method to the current practice of using GWPs, or other metrics such as those that consider temperature change. In addition, practitioners who elect to use TAWPs should consider the recommendations of Brandão and Levasseur (2011) and test the outcome at both short and long analytical time horizons.

One challenge for using the TAWP or any new metric for interpreting previous studies is the lack of detail regarding the timing of emissions and the breakdown of CO_2e emissions into constituent GHGs which prevails in current and previous studies. Thus, if the TAWP, other methods addressing emissions timing, or alternative metrics for characterizing the effects of GHGs are to be adopted in LCA and carbon footprinting methods, additional detail in reporting is required.

Conclusions regarding the importance of short lived climate-forcing agents, particularly when shorter analytical time horizons are considered (Peters et al. 2011), suggests that the TAWP model should be expanded to include these emissions.

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